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# Soil microbial activity, nitrogen cycling, and long-term changes in organic carbon pools as related to fallow tillage management

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**Abstract**

Two experiments were established in 1969 and 1970 near Sidney, NE, to determine the effect of moldboard plow (plow), sub-tillage (sub-till), and no-tillage (no-till) fallow management on soil properties, biological activities, and carbon and nitrogen cycling. One experiment was on land which had been broken from sod in 1920, seeded to crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.] from 1957 to 1967, and cultivated for wheat again in 1967 (Previously Cultivated site). The second experiment was established on land that was in native mixed prairie sod until 1969 (Native Sod site), and compared the three tillage management practices listed above in a winter wheat-fallow system as well as replicated plots remaining in sod. Soil sampling done 10–12 years after these experiments were initiated, indicated that the biological environment near the soil surface (0–30 cm) with no-till was often cooler and wetter than that with conventional tillage management practices, especially moldboard plowing. Biological activity and organic C and N reserves were concentrated nearer the soil surface (0–7.6 cm) with no-tillage, resulting in greater potential for tie-up of plant available N in organic forms. However, regardless of tillage practice with wheat-fallow management at either site, long-term (22–27 years) losses of soil organic C from surface soil (0–30 cm) ranged from 12 to 32% (320–530 kg C $ha^{-1}$ $year^{-1}$), respectively, for no-till and plowing. These soil C losses were closely approximated by losses measured to a depth of 122 cm, indicating that under the cropping, tillage, and climatic conditions of this study, soil C changes were adequately monitored by sampling to a depth of 30 cm within which most C loss occurs. No-till management maintains a protective surface cover of residue and partially decomposed materials near the soil surface. However, the decline in soil organic matter, and associated degradation in soil quality, will likely only be slowed by increasing C inputs to soil through use of a more intensive cropping system which increases the time of cropping and reduces the time in fallow. © 1998 Elsevier Science B.V. All rights reserved.

*Keywords:* Microbial C and N transformations; Fallow tillage management; Carbon sequestration; Soil quality

## 1. Introduction

Historically, shifts to reduced and no-tillage management for production of wheat (*Triticum aestivum* L.) in the USA were fostered by needs to decrease soil

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erosion and loss of organic matter, reduce fuel and labor costs, and conserve soil water as compared with conventional fallow tillage management. The increase in soil water conserved presumably reduces some of the risk in farming semi-arid and arid regions. Recent interest in maintaining soil quality has been stimulated by a renewed awareness of the importance of soil condition to both the sustainability of agricultural production systems and environmental quality (Doran and Parkin, 1996; Doran et al., 1996). Soil organic matter is an important component of soil quality as it determines many soil characteristics such as nutrient mineralization, aggregate stability, trafficability, and favorable water uptake and retention properties. Recent concern over world-wide climate change has also increased interest in soil organic matter and its role in the global C budget through sequestration of atmospheric C in soil.

Use of herbicides in place of tillage for control of weeds with winter wheat in the US Central Great Plains conserves an additional 2.5–15 cm of water during fallow, however, this is not always reflected by corresponding increases in yield with reduced tillage (Smika and Wicks, 1968; Wicks and Smika, 1973; Fenster and Peterson, 1979). Thus, the greater yield potential created by additional water conservation with reduced tillage is lessened by other changes in the soil environment or crop management practices associated with no-till. Early researchers noted influences of different tillage practices on nitrate nitrogen ($NO_3^-$–N) levels in soil and its effect on wheat yields (Call, 1914; Sewell and Call, 1925). More recent research in western Nebraska demonstrated lower soil ($NO_3^-$–N) levels with reduced and no-tillage (no-till) during the first 8–10 years after changing from conventional tillage systems (Fenster and Peterson, 1979). Initial changes in soil microbial activity and N cycling may account, at least in part, for lower than expected initial crop yields with reduced and no-till systems (Broder et al., 1984).

The biological environment of soil is greatly modified by type and degree of tillage. In a survey of tillage studies at several locations in the United States, no-till soils were generally wetter and less aerobic than plowed counterparts, especially in humid climates (Doran, 1980; Doran and Linn, 1994). Soil microbial populations and enzyme activities were greater with no-till and the amount of potentially mineralizable N in the surface 7.5 cm of no-till soils averaged 35% greater than in plowed soils, thereby indicating a greater conservation of N in organic forms. Increased soil-microbial populations, stimulated by greater organic matter and water contents with reduced tillage, could compete with the crop for available N. Also, soil denitrifier populations of no-till soils were significantly greater than those of plowed soils. Higher soil water contents in no-till soils result in greater denitrification rates as compared with plowed soils (Aulakh et al., 1982; Rice and Smith, 1982; Aulakh et al., 1992), which could also result in a loss of plant available $NO_3^-$–N.

The objective of this research was to evaluate and review the short-term (10–12 years) effects of fallow tillage management on the size of microbial biomass pools in soil, the activity of N metabolizing microorganisms (denitrifiers, nitrifiers, etc.), and the distribution of organic C, organic N, and potentially mineralizable N in surface soil. These biological characteristics were also compared with the soil water content and available N levels ($NH_4^+$ and $NO_3^-$) as influenced by fallow tillage management. A second objective of this research was to evaluate the long-term effects of fallow tillage management on soil organic C pool levels as influenced by microbial processes and C inputs.

## 2. Materials and methods

### *2.1. Site descriptions*

The two sites chosen for this study are located at the High Plains Agricultural Research Lab near Sidney in western Nebraska. Mean annual precipitation is 446 mm (mainly as rainfall), of which 63% occurs between April and July. The two sites differ in both soil type and cultural history.

The first site, referred to as the Previously Cultivated site, was on an Alliance silt loam (fine silty, mixed, mesic Aridic Argiustolls; FAO- Luvic Kastanaozem), was cultivated for 37 years prior to being seeded to crested wheatgrass in 1957. In 1967, the crested wheatgrass was plowed down and the field was divided into two sections (Tillage A and B), one seeded to winter wheat and the other section left fallow. In this way, one section was cropped to wheat every year of the wheat/fallow rotation. The major fallow management practices under study were plowing (plow), sub-tillage (sub-till) and no-tillage (no-till). For the plowing treatment, a moldboard plow was used to a depth of 10–15 cm in the spring, followed by 3–5 operations with a field cultivator, disk, or rotary rodweeder. Sub-till operations were performed with 0.9 or 1.5 m sweeps at a depth of 10–15 cm two to four times a year followed by 1 or 2 rotary rodweeder operations. The no-till treatment received only herbicides for weed control and placement of the seed at planting was the only operation that caused soil disruption. Wheat on all tillage treatments received either 0 or 45 kg N $ha^{-1}$, broadcast as $NH_4NO_3$ in April, during cropping. A split plot design was used with three tillage treatments as main plots and two N rates as sub-plots, with four replications. Field plots were 8.5 m×76 m in size, row spacing for wheat was 30.5 cm.

The second site, referred to as the Native Sod site, was on a Duroc loam (fine silty, mixed, mesic Pachic Haplustolls; FAO- Haplic Kastanaozem), which had never been cultivated prior to being plowed in 1969 and seeded to wheat in 1970. This field was also divided into two sections (Tillage C and Tillage D) to accommodate the wheat/fallow rotation. The same tillage treatments were employed as mentioned for the Previously Cultivated site. In addition, one plot per replicate was left in native sod, a mixture of native prairie species, to serve as a control for evaluation of changes in soil properties. Experimental design was a randomized complete block with three replicates. Experimental plots were 8.5 m wide and 45.7 m long. No fertilizer N was applied at this site. A more detailed description of cultural practices for both sites is given by Fenster and Peterson (1979) and by Lyon et al. (1998).

### 2.2. Soil analyses

Soils were sampled with a 2 cm diameter probe to a depth of 30.5 cm in increments of 0–7.6, 7.6–15.2, and 15.2–30.5 cm, generally during the spring, summer, and autumn of the cropped year. Each sample consisted of 10 to 14 subsamples composited for like depths within each plot. Analyses of soils (<2 mm sieve) for total C, total N, and soil enzymes were performed as described by Doran (1980). Soil organic C values for samples taken prior to 1983 were calculated by assuming that C extracted by the wet digestion technique (Walkley–Black) recovered 77% of the total organic C (Schulte, 1988). After 1985, total soil C and N were determined by the Dumas dry combustion technique using an automated Carlo Erba NA 100 C and N analyzer interfaced to a Europa Tracermass mass spectrometer[1] as described by Schepers et al. (1989). Soil organic C contents were calculated by subtracting carbonate C contents from total C values when soil pH values exceeded by 7.2, which indicates the presence of carbonates. Methods for determining soil nitrifier and denitrifier populations (most probable number technique), soil water content, $NH_4^+$ and $NO_3^-$ contents, and potentially mineralizable nitrogen (PMN) levels have been described elsewhere (Broder et al., 1984). Soil microbial biomass levels were determined using the chloroform fumigation/incubation technique of Jenkinson and Powlson (1976) as modified by Doran (1987). All soil physical, chemical, and biological soil properties were converted to a volumetric basis using the measured soil bulk density of each tillage management treatment as described by Mielke et al. (1986).

Intact soil cores were used to estimate soil respiration, soil denitrification, and non-symbiotic N fixation activities as described by Fraser et al. (1988). Soil temperatures at the previously cultivated site were monitored using thermocouples installed at the 5 cm depth in soil as described by Culik et al. (1982). At the Native Sod site, soil temperatures at a 5 cm depth and air temperatures were monitored using bi-metal minimum/maximum thermometers (Weksler Instruments, Freeport, NY).[2]

Soil sampling to a depth of 1.2 m was accomplished using a tractor hydraulic probe fitted with a 3.8 or 4.4 cm diameter coring tube. In the south half of each plot, two profile cores were taken in a line parallel with the direction of row orientation at 12 and 15 m in from the east border of each plot. These two samples were

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composited by sampling depths of 0–15.2, 15.2–30.5, 30.5–61, 61–92, and 92–122 cm. The dry weight of soil was determined for each sampling depth and soil bulk density was determined using the volume of soil contained in each sample as determined by the inside diameter of the coring tube cutting edge and length of each sampling increment. Adjustments were made, or resampling was done, when soil compacted during sampling. Surface soil bulk densities determined by this method were essentially the same as soil bulk densities determined for the surface 0–7.6, 7.6–15.2, and 15.2–30.5 cm depths by standard techniques referred to previously. Soils were subsampled and passed through a 2 mm sieve before being analyzed for physical and chemical determinations as detailed earlier.

Soil samples from the Native Sod site were also taken during the fallow periods in 1992 and 1993 as part of a project sponsored by the U.S. Environmental Protection Agency. This site was sampled in the spring of 1992 or 1993 prior to cultural operations (Elliott et al., 1994). Six 5.6 cm$\times$20 cm cores were collected to a depth of 1.2 m and composited from each field replicate using a truck-mounted hydraulic soil exploration probe. Immediately after collection, soil samples were put on ice for transport to the laboratory. Surface (0–20 cm) samples used in biological analyses were stored at 4°C for not more than 24 h and seived moist to pass a 2 mm screen prior to incubation, remaining samples were air-dried, crushed and sieved. Crop residues, roots, and rock fragments within each sample were removed, dried and weighed. Total C and N were determined by dry combustion of duplicate subsamples from each depth of each treatment replicate on a Carlo Erba CHN analyzer Model 1104 (Carlo Erba Instruments, Milano, Italy).[3] Soil texture and particulate soil organic matter (POM) were determined according to a modified version of the Cambardella and Elliott (1992) method. Briefly, POM was isolated by dispersing 10 g soil samples in 0.5% sodium hexametaphosphate and passing the dispersed soil samples through a 53 μm sieve, which retains the POM fraction and allows the mineral-associated fraction to pass through. The sand plus POM fraction were dried (50°C), finely ground and subsampled for total organic C and N. The soil slurry passing through the sieve was transferred to a 1 l sedimentation cylinder and the silt and clay content determined using the hydrometer method. Soil pH was determined on duplicate 10 g samples using a 1:2 soil:water ratio.

Analysis of variance and Duncan's Multiple Range procedures were used for statistical analyses of experimental results. Effects of N application for the previously cultivated site were analyzed using a split plot design. Fishers protected least significant difference ($P$<0.05) was used for mean separation of long-term changes in soil organic carbon.

## 3. Results and discussion

### *3.1. Initial comparisons (first 10–12 years)*

The information presented here is primarily a compilation of research results which have not been previously published and were collected or compiled to address research questions remaining after publication of the initial results at these research sites.

#### *3.1.1. Soil C and N pools*

Fallow tillage management practices greatly influenced the content and distribution of organic matter in soil. As illustrated in Table 1, organic C and N contents of surface soil (0–7.6 cm) with plowing declined by 11–27% at the Previously Cultivated site and 35–40% at the Native Sod site over an 11-year period. The greater relative decline for the Native Sod site reflects the greater initial soil organic matter content at that site which was undisturbed by previous cultivation, and a greater relative dilution effect resulting from mixing with soil of lesser soil organic matter content at deeper depths during tillage. No-till management resulted in the least loss of C and N from this depth with time which is consistent with accumulation and maintenance of organic matter near the soil surface. Changes in surface soil C and N can result from several mechanisms: (i) redistribution, mixing, and dilution with depth due to tillage; (ii) biological oxidation of soil organic matter; (iii) reductions in C and N inputs to soil due to changes in plant inputs due to crop and fallow management; and (iv) erosion

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Table 1
Soil total carbon and nitrogen contents at four depth intervals (cm) as affected by previous management and fallow tillage practice after 11 years at Sidney, Nebraska

| Site and previous management, fallow tillage[a] | Total organic C | | | | Total Kjeldahl N | | | |
|---|---|---|---|---|---|---|---|---|
| | 0–7.6 (Mg C $ha^{-1}$) | 7.6–15.2 | 15.2–30.5 | 0–30.5 | 0–7.6 (Mg N $ha^{-1}$) | 7.6–15.2 | 15.2–30.5 | 0–30.5 |
| *Previously cultivated*[b] | | | | | | | | |
| Initial (1969) | 14.2 | 12.3 | 18.5 | 45.0 | 1.08 | 0.86 | 1.78 | 3.74 |
| Plow | 10.4* | 10.7 | 14.3 | 35.4 | 0.96 | 1.02 | 1.81 | 3.79 |
| Sub-till | 12.2 | 10.0 | 12.4 | 34.6 | 1.08 | 1.05 | 1.66 | 3.78 |
| No-till | 13.7* | 9.8 | 12.0 | 35.5 | 1.20* | 0.98 | 1.62 | 3.80 |
| *Native Sod* | | | | | | | | |
| Plow | 15.3* | 16.3 | 22.2 | 53.8 | 1.19* | 1.26 | 1.89 | 4.34 |
| Sub-till | 18.3* | 16.8 | 20.0 | 55.1 | 1.41 | 1.31 | 1.50 | 4.22 |
| No-till | 20.5* | 15.1 | 21.1 | 56.7 | 1.54 | 1.23 | 1.64 | 4.41 |
| Sod | 25.6* | 15.9 | 21.3 | 62.8* | 1.83* | 1.24 | 1.66 | 4.78* |

[a] Previously cultivated site (Tillage A) sampled on 13 May 1980 and Native Sod site (Tillage D) sampled on 22 September 1981.
[b] Means represent averages for non-fertilized and fertilized (45 kg N $ha^{-1}$) treatments (no significant effect of N fertilization).
* Treatment mean within site and soil depth differs significantly between management practice at $P<0.05$.

loss from and deposition on surface soil. Redistribution of organic matter is demonstrated by comparisons of soil N contents over the surface 30.5 cm depth interval, where little or no change in total N with time has occurred at the Previously Cultivated site (where fertilizer N was added) and only an 8% decline has occurred at the Native Sod site (with little effect of tillage management). Organic C in the surface 0–30.5 cm of soil, which can be lost to the atmosphere as $CO_2$ through biological oxidation of soil organic matter, declined 21–23% at the Previously Cultivated site and 10–14% at the Native Sod site as a result of tillage and cropping to wheat. There was little difference in C decline due to fallow tillage management at the Previously Cultivated site, but at the Native Sod site declines were greater with increasing degree of tillage intensity and resulted predominantly from losses in surface (0–7.6 cm) soil. Losses of surface soil C and N are greatest during the first 8–10 years after a sod is cultivated and the rate of loss declines with time thereafter (Peterson and Vetter, 1971; Campbell et al., 1976).

In our study, loss of surface soil (0–7.6 cm) organic matter with time and increasing degrees of tillage at the Native Sod site were negatively correlated with soil bulk density. As illustrated in Fig. 1, each percent decline in soil organic C concentration was associated with a 0.12 unit increase (about 10%) in soil bulk density. Greater surface soil sand contents in tilled (about 42% sand for plow and sub-till) than non-tilled soils (34–35% sand for sod and no-till) also contributed to variation in soil bulk density. These relative differences in soil bulk density as related to tillage management were closely predicted using the model of Rawls (1983) which predicts changes in soil bulk density within soil textural classes as a function of soil organic matter content. These data demonstrate the need to convert gravimetric soil analyses to a volumetric basis, using measured soil bulk densities at the time of sampling, for valid comparison and interpretation of tillage management effects where soil organic C contents differ considerably. Apparent losses of soil organic C from surface soil in this study were 40–60% greater when results were expressed on a gravimetric basis (Follett and Schimel, 1989). Due to a lesser initial organic C content (1.14%) at the previously cultivated site, surface soil (0–7.6 cm) bulk densities varied little between tillage management practices and ranged from 1.25 to 1.29 Mg $m^{-3}$.

Part of the decline in surface soil organic matter at the Sidney Native Sod site may have resulted in part from wind erosion and loss of the fine earth fraction. O'Halloran et al. (1987) conducted extensive sampling of surface soils (0–15 and 0–20 cm) at this site

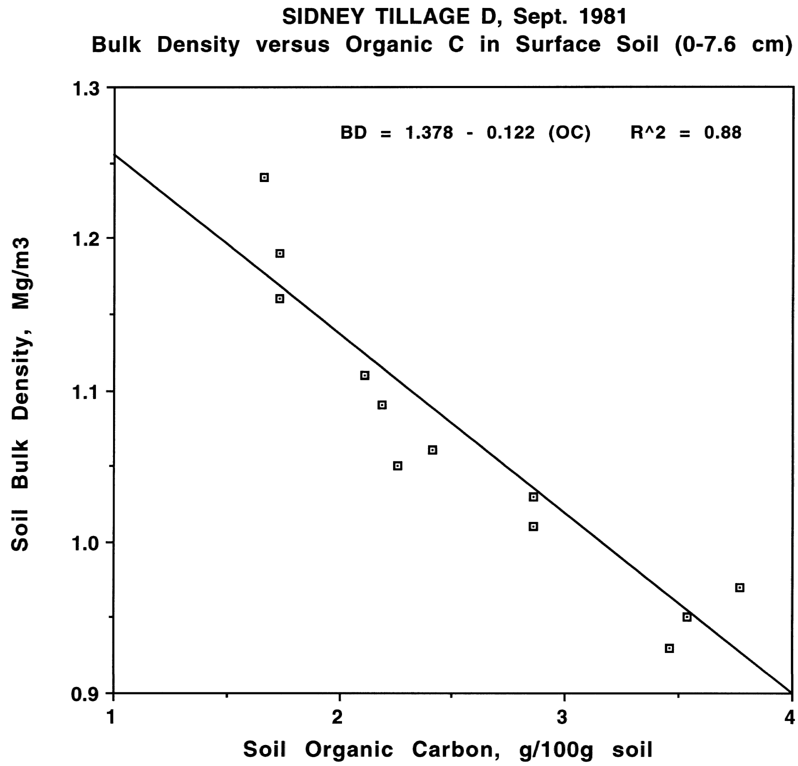


Fig. 1. Relationship between bulk density and organic C concentration for surface soils (0–7.6 cm) from the Sod (avg. bulk density=0.95 Mg $m^{-3}$), No-till (avg. bulk density=1.03 Mg $m^{-3}$), Sub-till (avg. bulk density=1.09 Mg $m^{-3}$), and Plow (avg. bulk density=1.20 Mg $m^{-3}$) treatments of the Native Sod site (Tillage D) in September, 1981.

and estimated, from textural and $^{137}$Cesium analyses, that erosion losses of the 0–15 cm soil depth ranged from 15–40%, 15–20% and <5% on the plow, sub-till, and no-till management systems, respectively. No erosion had occurred on the native sod treatment and there was some evidence that soil material had been deposited on the side of the grassed areas adjacent to plowed soil.

### 3.1.2. Microbial activity and N cycling

Changes in soil organic matter content and distribution with different tillage management practices influence microbial populations and activity through changes in substrate supply, water relations, and associated soil physical changes. This is demonstrated by differences in soil enzyme activities with tillage management practices at the two sites (Table 2). The greatest effect of tillage management occurs in the surface 0–7.6 cm of soil and parallels differences in soil organic matter and soil water content (Doran and Power, 1983). Soil dehydrogenase and phosphatase are indices of the levels of activity of microbial populations and these results suggest greater microbial activity in the surface of no-till and sub-till compared with plowed soils. These enzyme measurements were among the most sensitive indicators of treatment differences within the first 10 years of this study.

During 1979 and 1980, the populations of N metabolizing microorganisms, available N forms, potentially mineralizable N (PMN), and soil water contents were monitored during the spring growing season at the two sites to evaluate the influence tillage management might have on N availability to winter wheat (Broder et al., 1984). Nitrifier and denitrifier populations and available N levels in soil were significantly influenced by tillage management practices imposed 8–12 months earlier. Relative comparisons of microbial and chemical properties between tillage practices

Table 2
Soil enzyme activity and water content at two soil depths during the cropping season as influenced by fallow tillage management at previously cultivated and native sod sites

| Site and previous management, fallow tillage[a] | Dehydrogenase[b] | | Phosphatase[b] | | Water content | |
|---|---|---|---|---|---|---|
| | 0–7.6 cm | 7.6–15.2 cm | 0–7.6 cm | 7.6–15.2 cm | 0–7.6 cm | 7.6–15.2 cm |
| | (mg formazan 6 $cm^{-3}$ soil 24 $h^{-1}$) | | (μmoles PNP $cm^{-3}$ soil $h^{-1}$) | | (g $cm^{-3}$ soil) | |
| *Previously cultivated* | | | | | | |
| Plow | 0.09 b* | 0.10 a | 4.2 b | 5.8 a | 0.31 b | 0.29 b |
| Sub-till | 0.09 b | 0.12 a | 5.1 ab | 6.4 a | 0.31 ab | 0.31 a |
| No-till | 0.12 a | 0.11 a | 5.9 a | 6.4 a | 0.34 a | 0.31 a |
| *Native Sod* | | | | | | |
| Plow | 0.32 c | 0.32 c | 8.1 c | 11.7 b | 0.27 b | 0.28 a |
| Sub-till | 0.42 bc | 0.32 c | 9.4 bc | 11.0 b | 0.26 b | 0.25 b |
| No-till | 0.49 b | 0.36 b | 9.8 b | 13.2 ab | 0.30 a | 0.27 ab |
| Sod | 0.71 a | 0.50 a | 12.9 a | 15.1 a | 0.26 b | 0.25 b |

[a] Previously cultivated site (Tillage A) sampled on 6 June, 1978 and Native Sod site (Tillage D) on 7 June, 1978.
[b] Enzyme activities assessed by measuring formation of triphenol formazan and *p*-nitrophenol (Doran, 1980).
* Treatment means within site and depth followed by the same letter do not differ significantly at $P<0.05$.

Table 3
Relative differences in N metabolizing microorganisms and soil nitrogen properties between reduced tillage and plowed systems for the surface 0–15.2 cm of soil at two sites during spring of 1979 and 1980 (after Broder et al., 1984)

| Site tillage comparison | Ratio, reduced tillage/plowing[a] | | | | | | |
|---|---|---|---|---|---|---|---|
| | $NH_4^+$ oxidizers | $NO_2^-$ oxidizers | Denitri-fiers | Water content | $NH_4^+$–N | $NO_3^-$–N | PMN |
| *Previously cultivated* | | | | | | | |
| No-till/plow | 0.54* | 0.78* | 13.0 | 1.13* | 1.22 | 0.80* | 1.20* |
| | (0.65*)[b] | (0.80) | (1.9) | (1.11*) | (0.95) | (0.78*) | (1.39*) |
| Sub-till/plow | 0.67* | 0.84* | 8.7 | 1.03 | 1.11 | 0.88 | 1.12* |
| | (0.78) | (0.83) | (2.4) | (1.05*) | (0.95) | (0.96) | (1.33) |
| *Native Sod* | | | | | | | |
| Sod/plow | 0.35* | 0.64* | 4.3 | 1.14* | 1.95* | 1.07 | 0.93 |
| No-till/plow | 0.44* | 0.77* | 1.5 | 1.03 | 0.91 | 1.09 | 1.05 |
| Sub-till/plow | 0.65* | 0.69* | 2.8 | 1.04 | 1.26 | 1.01 | 1.02 |

[a] Average of ratios for 17 April, 23 May, and 27 June, 1979 and 17 April and 13 May, 1980 at the Previously Cultivated site and 19 April and 27 June, 1979 and 08 June, 1980 at the Native Sod site.
[b] Values in parentheses at the previously cultivated site received 45 kg N $ha^{-1}$; values not in parentheses did not receive N.
* Difference between tillage treatments significant at the 0.10 or 0.05 (*) levels of probability by Duncan's multiple range test.

at the two sites are given in Table 3 and are summarized for the 0–15.2 cm soil depth, because this was the major zone of microbial activity. Microbial populations at the 15.2–30.5 cm depth (data not shown) were one to two orders of magnitude less than those at the surface and although significant differences between tillage practices occurred at this depth, their relevance to net N transformations was questionable. At both sites, populations of nitrifiers in no-till and sub-till soils averaged 22–56% and 16–35% lower, respectively, than in plowed soil. Denitrifier populations tended to increase as degree of tillage was reduced. Addition of $NH_4NO_3$ fertilizer had little influence on relative comparisons among tillage treatments at the Previously Cultivated site. During the fallow season, Kruglov et al. (1979) attributed lower nitrifier populations for no-till soil, as compared to sub-till and plowed soils, to reduced mixing of wheat residues with soil and to inhibition of nitrifiers by herbicides used for no-till. In our study, herbicide inhibition of nitrifiers was unlikely, because herbicides were applied over 9 months before sampling at rates which were two orders of magnitude below levels which inhibit nitrification (Goring and Laskowski, 1982). However, it is possible that, nitrifier populations are outcompeted or suppressed by greater activity of heterotrophic populations in the reduced-tillage systems.

Differences in soil temperature and water content, as related to changes in surface residue cover, appear to be major factors responsible for differences between tillage treatments in nitrifier and denitrifier populations. Temperatures for bare soil (5 cm depth) continuously recorded near the sites averaged 9.6°C, 15.9°C, and 23.7°C for April, May, and June of 1979 and 1980 (data not shown). Temperatures of straw-covered (no-till) and sod-covered soil for the same periods averaged 1–2°C cooler than those for bare soil (tilled soil). Soil temperature at both experimental sites from 1981 to 1983 followed a similar pattern with median temperatures for no-till management averaging 1–2°C cooler than with plowing. Average maximum soil temperatures with no-till, however, were up to 5°C cooler than those with plowing. A 1–2°C difference in soil temperatures during spring when suboptimal temperatures prevail can significantly influence mineralization and nitrification activity (Sabey et al., 1956; Malhi and McGill, 1982).

As illustrated in Table 3, concentrations of $NO_3$–N in no-till soil at the Previously Cultivated site averaged 20–22% less than those in plowed soil and reflected differences in nitrifier and denitrifier populations and possibly immobilization. There was little difference in seasonal soil $NO_3$–N levels at the Native Sod site. At the Previously Cultivated site, levels of potentially mineralizable N (PMN) for the 0–15.2 cm depth in no-till and sub-till soils averaged 20–39% and 12–33% greater, respectively, than in plowed soil. Greater levels of PMN with reduced tillage reflect either greater immobilization, less mineralization, or both as compared with plowing. There was no seasonal difference in $NO_3$–N or PMN levels between tillage practices at the Native Sod site. Soil organic N was significantly greater with reduced tillage than with plowing at this site (Table 1) and could have easily masked differences in net mineralization of N among tillage practices. Also, the effects of lower soil bulk densities, indicative of higher organic matter, could have reduced denitrification losses of N because of increased soil porosity and aeration for all treatments.

This and other research indicated that the type of fallow tillage management changed the relative predominance and distributions of microbial populations in soil (Broder et al., 1984; Doran and Linn, 1994). These biological differences were also associated with changes in soil water content, plant available N, and soil organic matter contents. In 1982 and 1983, intact cores were taken from the Native Sod site to evaluate if these population changes might be related to changes in microbial activities related to N cycling. As illustrated in Table 4, soil respiration was generally greater with no-till or sub-till as compared with plowing. This probably resulted from more optimal water contents for microbial activity and greater amounts of substrate available for microbial activity with no-till and sub-till as compared with plowing. Temperature was not a factor in this study, since, all assays with intact cores were performed in the laboratory at 25°C. Results for soil denitrification demonstrated fewer differences between tillage management, but activity was positively correlated with soil water content ($P<0.05$). Significant amounts of denitrification would only be expected at high soil water contents which would only occur over very short periods in the year. Soil $N_2$ fixing activity was significantly higher with no-till compared with plowing in April and June in cropped and fallow soils, but still amounted to less than 1 kg N $ha^{-1}$ fixed during one cycle of the winter wheat-fallow rotation (Lamb et al., 1987). Soil $N_2$ fixing activity was positively correlated ($P<0.05$) with soil water content. In September when soils were drier, few differences were observed. Thus, tillage and residue management indirectly influence microbial activity primarily by regulating soil water contents. The importance of soil organic matter and perhaps exudates and debris from plant roots is suggested by the greater levels of soil microbial activity observed with grass sod. The large increase in soil $NO_3$–N contents in September for both cropped and fallow soils suggests a large flush of mineralization of N from some organic N pool, perhaps related to soil drying.

Soil microbial biomass can serve as both a sink and source for plant available N depending, in part, on levels of available C and soil water status. Levels of

Table 4
Biological activity and nitrate and water contents in intact soil cores (surface 0–7.6 cm) as influenced by tillage management practice, time of year, and cropping, Native Sod site, 1983

| Soil measurement, fallow tillage | Soil measurement or biological activity during cropping or fallow* | | | | | |
|---|---|---|---|---|---|---|
| | Cropped (tillage C) | | | Fallow (tillage D) | | |
| | April | June | Sept | April | June | Sept |
| *Water content* | ($g\ cm^{-3}$) soil | | | | | |
| Plow | 0.16 d | 0.27 b | 0.16 ab | 0.21 c | 0.19 c | 0.16 b |
| Sub-till | 0.20 c | 0.29 ab | 0.21 a | 0.22 b | 0.22 b | 0.19 a |
| No-till | 0.24 b | 0.32 a | 0.21 a | 0.26 a | 0.25 a | 0.18 a |
| Sod | 0.28 a | 0.28 ab | 0.13 b | 0.28 a | 0.27 a | 0.12 c |
| *Respiration* | ($kg\ CO_2\ ha^{-1}\ d^{-1}$) | | | | | |
| Plow | 12 b | 15 c | 11 b | 12 c | 15 b | 10 b |
| Sub-till | 37 b | 46 b | 17 ab | 27 b | 23 b | 22 a |
| No-till | 28 b | 43 b | 23 a | 42 b | 21 b | 13 b |
| Sod | 106 a | 75 a | 13 ab | 99 a | 75 a | 12 b |
| *Denitrification* | ($g\ N_2O\ ha^{-1}\ d^{-1}$) | | | | | |
| Plow | 12 b | 12 a | 0 a | 8 c | <1 b | 0 a |
| Sub-till | 30 b | 29 a | 4 a | 31 b | 1 b | <1 a |
| No-till | 45 b | 14 a | 3 a | 66 b | 6 b | <1 a |
| Sod | 235 a | 29 a | 0 a | 123 a | 49 a | 0 a |
| *N fixation* | ($g\ N_2\ ha^{-1}\ d^{-1}$) | | | | | |
| Plow | 1.9 c | 3.4 b | 0.7 a | 6.0 b | 1.5 b | 1.5 a |
| Sub-till | 2.9 bc | 4.3 ab | 0.6 a | 5.5 b | 2.2 ab | 1.0 b |
| No-till | 4.8 b | 6.3 a | 0.5 a | 8.5 a | 3.4 a | 0.6 b |
| Sod | 7.2 a | 3.6 b | 0.5 a | 16.1 a | 5.5 a | 0.6 b |
| *Nitrate content* | ($kg\ NO_3–N\ ha^{-1}$) | | | | | |
| Plow | 4 b | 3 b | 25 a | 4 c | 4 b | 28 b |
| Sub-till | 5 b | 3 b | 33 a | 5 bc | 4 b | 35 b |
| No-till | 6 b | 4 ab | 28 a | 6 ab | 7 a | 58 a |
| Sod | 8 a | 5 a | 5 b | 7 a | 4 b | 2 c |

* Treatment means within date followed by different letters differ significantly at $P<0.05$.

soil microbial biomass between tillage management practices were similar at the Previously Cultivated site (Table 5). At the Native Sod site, however, microbial biomass levels were greatest where the degree of soil disturbance was lowest and least where the soil was plowed. Influences of tillage management on microbial biomass were predominantly limited to the surface 0–7.6 cm of soil. As mentioned earlier this is also the layer of soil, where differences in soil organic matter and water content between tillage management practices were greatest. Microbial biomass levels at both the Previously Cultivated and Native Sod sites were highly correlated with soil C and N contents ($r$=0.885 to 0.950, $P$<0.001). Amount of N contained in microbial biomass in the surface 0–7.6 cm layer of soil at the Native Sod site during cropping (assuming a biomass C/N ratio of 8.5 to 1) ranged from 79 kg N $ha^{-1}$ for plow to 109 kg N $ha^{-1}$ for no-till. Higher levels of surface soil microbial biomass with reduced tillage were also observed during fallow although levels for all management practices were significantly less than when cropped. Part of this effect was probably related to the crop supplying substrates for microbial growth. Lower biomass levels observed during fallow on the sod plots suggest time of year and possibly soil water content, were important determinants of soil biomass levels.

Reserves of potentially mineralizable N (PMN) in soil were also influenced by tillage management (Table 6). At the Previously Cultivated site, PMN

Table 5
Soil microbial biomass levels as influenced by previous management and fallow tillage management

| Site and previous management, fallow tillage | Microbial biomass at four depth intervals (cm)[*] | | | |
|---|---|---|---|---|
| | 0–7.6 (kg C $ha^{-1}$) | 7.6–15.2 | 15.2–30.5 | 0–30.5 |
| *Previously cultivated*[a] | | | | |
| Plow | 364 a | 373 b | 525 a | 1261 a |
| Sub-till | 377 a | 407 a | 589 a | 1372 a |
| No-till | 430 a | 421 a | 529 a | 1381 a |
| *Native Sod*[b] | | | | |
| – Cropped | | | | |
| Plow | 669 c | 764 ab | 1074 a | 2508 b |
| Sub-till | 828 b | 668 b | 992 a | 2488 b |
| No-till | 929 b | 688 b | 1056 a | 2673 b |
| Sod | 1053 a | 851 a | 1145 a | 3049 a |
| – Fallow | | | | |
| Plow | 385 c | 441 a | 596 a | 1422 c |
| Sub-till | 604 b | 472 a | 578 a | 1655 b |
| No-till | 713 b | 428 a | 587 a | 1728 b |
| Sod | 931 a | 474 a | 642 a | 2047 a |

[a] Average of fertilized (45 kg N $ha^{-1}$) and non-fertilized plots in tillage B for May 1981.
[b] Sampled in wheat on 15 April, 1981 in Tillage C and at end of fallow on 22 September, 1981 in Tillage D.
[*] Means within site and depth followed by different letters differ significantly at $P<0.05$.

levels in non-fertilized surface soils were greatest with no-till and least with plowing. There were no differences in PMN between tillage management practices where soils were fertilized with 45 kg N $ha^{-1}$ of $NH_4NO_3$. Since, there was no significant effect of fertilization on soil microbial biomass levels, these results suggest a greater potential for converting plant available soluble N to organic forms (microbial biomass) with no tillage. This conclusion is supported by findings of Follett and Schimel (1989) from laboratory studies using $^{15}N$ tracers and surface soils (0–10 cm) which were sampled in 1986 (during fallow) from the Native Sod tillage study and is consistent with results reported by Power and Peterson (1998). There was little difference in PMN at the Native Sod site except during fallow when levels in the 0–7.6 cm layer were highest with reduced tillage but at 7.6–30.5 cm were highest with plowing. Again, this suggests a redistribution of organic N reserves as a result of tillage management.

### 3.2. Long-term changes in soil C levels

As reported earlier by Lyon and Doran (1995), soil organic C levels continue to decline at this location in western Nebraska after over two decades of winter wheat-fallow management. As illustrated in Fig. 2, declines in C content are greatest near the soil surface (on a relative basis) but least with no-tillage management. This is consistent with accumulation and maintenance of soil organic matter near the soil surface with no-till and a reduction in loss by soil erosion. The reduction of organic C in surface soil (0–7.6 cm) at the Previously Cultivated site, after 27 years of winter wheat-fallow, ranged from 18% for no-till to 41% for plowing (Fig. 2(a)). Due to a greater initial C content, the reduction in surface soil organic C following tillage at the Native Sod site was slightly greater and ranged from 21% to 48% for the same fallow management systems (Fig. 2(b)). Effects of C redistribution due to tillage are illustrated by the organic C contents of the 0–30.5 cm soil layer for each site, which was well below the depth of tillage. Long-term decreases in organic C ranged from 26% to 32% for the Previously Cultivated site and 22–29% for the Native Sod site for the no-till and plow treatments. Decreases for sub-till management were between those for no-till and plow. These long-term decreases in surface soil C (over 27 and 22 years) correspond to average annual losses of 430–530 kg C $ha^{-1}$ $year^{-1}$

Table 6
Soil potentially mineralizable N (PMN) as influenced by fallow tillage management, N fertilization, and cropping

| Site and previous management, fallow tillage | Soil PMN at fourth depth intervals (cm)[*] | | | |
|---|---|---|---|---|
| | 0–7.6 (kg N ha$^{-1}$) | 7.6–15.2 | 15.2–30.5 | 0–30.5 |
| *Previously cultivated*[a] | | | | |
| – No N fertilizer | | | | |
| Plow | 74 c | 79 a | 102 a | 255 b |
| Sub-till | 86 b | 79 a | 86 b | 251 b |
| No-till | 96 a | 84 a | 83 b | 263 a |
| - Plus 45 kg N ha$^{-1}$ | | | | |
| Plow | 94 a | 78 a | 96 a | 268 a |
| Sub-till | 104 a | 81 a | 84 a | 269 a |
| No-till | 109 a | 78 a | 92 a | 279 a |
| *Native Sod*[b] | | | | |
| – Cropped | | | | |
| Plow | 102 a | 111 a | 148 a | 361 a |
| Sub-till | 102 a | 112 a | 164 a | 378 a |
| No-till | 117 a | 106 a | 160 a | 383 a |
| Sod | 112 a | 111 a | 166 a | 389 a |
| – Fallow | | | | |
| Plow | 97 b | 112 a | 148 a | 357 a |
| Sub-till | 111 a | 112 a | 130 b | 353 a |
| No-till | 115 a | 103 b | 138 b | 356 a |
| Sod | 107 ab | 98 b | 137 b | 342 a |

[a] Sampled while cropped to wheat on 12 May, 1981 (Tillage B) 3 weeks after fertilization.
[b] Sampled while cropped to wheat on 15 April, 1981 (Tillage C) and at end of fallow on 22 September, 1981 (Tillage D).
[*] Treatment means within depth followed by different letters differ significantly at $P<0.05$.

for the Previously Cultivated site and 320–530 kg C ha$^{-1}$ year$^{-1}$ for the Native Sod site (Tillage D). Few changes in soil organic C content (0–30.5 cm) between fallow management systems were noted at the Previously Cultivated site during the first 11 years. However, after 27 years, the decline in soil organic C appears to be leveling off and achieving a new equilibrium with no-till management. The decline in soil C in the surface 30.5 cm of the 'native' grass sod plots (Fig. 2(b)) between 1970 and 1992 may have resulted from a change in the native vegetation species and declining productivity, since these plots had not been grazed, hayed, or burned during this time period. Also, Follett et al. (1997) estimated, from differences in $^{13}$C signatures of surface soils sampled from the Native Sod plots in 1993 as compared to initial samples taken in 1972, that a major vegetation shift had occurred; from predominantly (70%) native $C_4$ grasses to a predominance (98%) of introduced $C_3$ grass species such as crested wheatgrass. Changes in C inputs to soil likely resulted from a change in productivity associated with the $C_3$ grass species. In contrast to our results for the surface 0–30.5 cm, however, Follett et al. (1997) reported that these changes led to an increase in C content in the surface 10 cm of soil on these sod plots. Thus, shifts in vegetation apparently change both the quantity of C inputs to soil and their relative distribution with depth in soil.

In addition to long-terms changes in the quantity of soil organic matter and related soil physical characteristics, it appears that quality of soil organic matter varies with tillage and cropping management as well. A greater proportion of total organic C or N pools are contained in the labile particulate organic matter pools (POM, defined as materials between 0.05 and 2 mm in size) in grassed soil or in reduced tillage soil cropped to wheat (Table 7). For surface soil (0–20 cm), the percentage of total organic C and N pools represented by POM ranged from 20% to 29% for grassed sod,

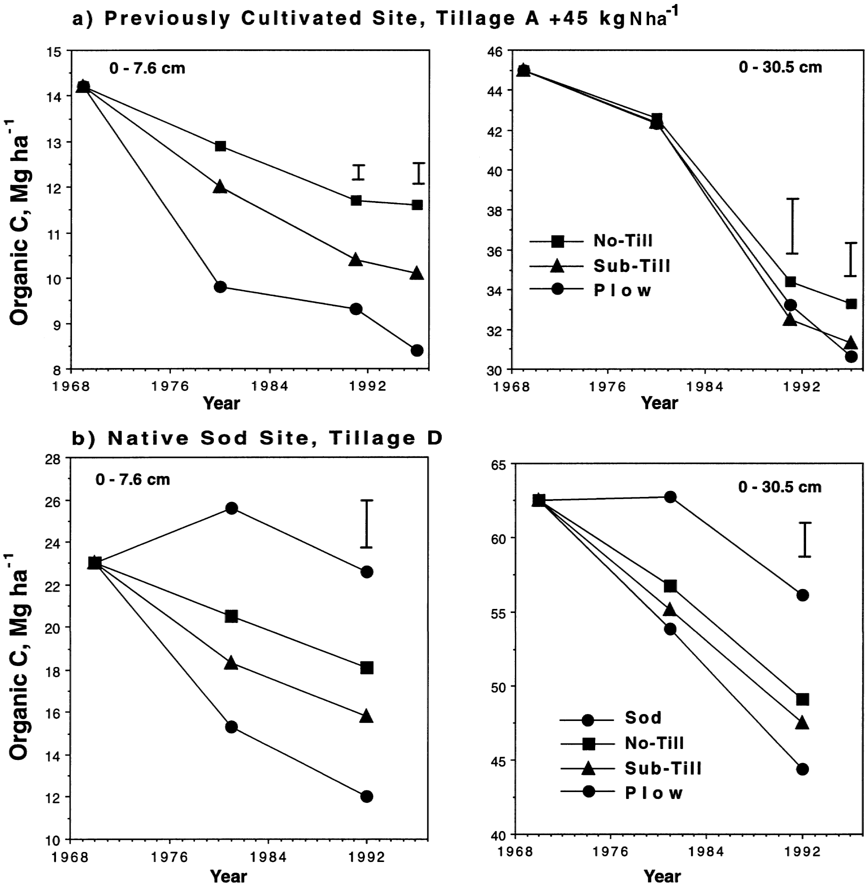


Fig. 2. Long-term changes in soil organic C contents, for the 0–7.6 cm and 0–30.5 cm soil depths, under varying winter wheat-fallow tillage management practices at two sites near Sidney, NE: (a) Previously Cultivated site (Tillage A, with 45 kg N $ha^{-1}$) and (b) Native Sod site (Tillage D). Bars above treatment means represent least significant differences among means at $P<0.05$.

14–22% for no-till wheat, 14–18% for sub-till wheat, and 13–18% for plowed wheat. Cambardella and Elliott (1992) obtained similar results for samples from this site and concluded that the POM fraction of soil organic matter is one of the most dynamic soil organic matter pools and more susceptible to loss when soils are cultivated and is lost more rapidly when derived from wheat than from grass.

For both sites in this study, the imposition of winter wheat-fallow management resulted in a 12–32% decline in soil organic C in the surface 0–30.5 cm of soil after 22–27 years, the lowest loss occurring with no-till and the greatest with plowing (Table 8). Similar results were obtained for samples taken to a depth of 122 cm in soil with winter wheat-fallow management showing a 6–28% loss in soil organic C, with losses generally being least with no-till and greatest with plowing. This finding confirms that the majority of soil organic C lost with winter wheat-fallow management systems resulted from losses from surface soil (0–30.5 cm), primarily from biological oxidation of soil organic matter and soil erosion. Results of this study also suggest that, C cycling was little influenced by changes in plant rooting density between winter wheat and grass at depths below 30 cm. Average annual losses of C from surface soil (0–30.5 cm), inferred from soil C changes over time, ranged from 430 to 530 kg C $ha^{-1}$ $year^{-1}$ at the Previously Cultivated site and from 320 to 530 kg C $ha^{-1}$ $year^{-1}$ at the Native Sod site, where

Table 7
Soil properties for 0–20 cm depth for the native sod site at Sidney, NE sampled during fallow for EPA carbon sequestration project

| Management treatments | Soil bulk density ($Mg\ m^{-3}$) | Particle size[a] | | | pH[b] | Organic | Total | $CO_3$–C | Particulate O.M. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Sand | Silt | Clay | | C[c] | N | | C | N |
| | | % by weight | | | | ($Mg\ ha^{-1}$) (20 cm) | | | | |
| *Tillage C* (sampled 4/27/1992) | | | | | | | | | | |
| Sod | 0.93 | 35 | 42 | 23 | 7.1 | 37 | 3.5 | 0.05 | 10.9 | 0.82 |
| No-till | 1.00 | 33 | 38 | 29 | 6.9 | 32 | 2.9 | 0.08 | 5.2 | 0.42 |
| Sub-till | 1.13 | 35 | 37 | 28 | 7.0 | 33 | 3.0 | 0.02 | 5.2 | 0.42 |
| Plow | 1.20 | 41 | 32 | 26 | 7.0 | 30 | 2.8 | 0.12 | 3.8 | 0.38 |
| *Tillage D* (sampled 4/27/1993) | | | | | | | | | | |
| Sod | 1.10 | 42 | 33 | 25 | 7.1 | 35 | 3.4 | 0.05 | 8.4 | 0.69 |
| No-till | 1.10 | 41 | 36 | 23 | 7.1 | 34 | 3.3 | 0.03 | 7.6 | 0.66 |
| Sub-till | 1.29 | 42 | 36 | 22 | 7.0 | 31 | 3.0 | 0.05 | 4.7 | 0.54 |
| Plow | 1.34 | 42 | 37 | 21 | 7.1 | 30 | 3.1 | 0.06 | 3.8 | 0.48 |

[a] Sand: 50–200 μm; Silt: 2–50 μm; Clay: <2 μm.
[b] pH of 1:2 soil:water mixture.
[c] Organic C: Total C$-CO_3$–C.

Table 8
Declines in surface and profile soil organic C as a result of wheat-fallow cropping and tillage management practices for the Previously Cultivated (Tillage A, +N) and Native Sod (Tillage C and D) sites at Sidney, Nebraska

| Condition or tillage practice | Organic C in surface soil and profile ($Mg\ C\ ha^{-1}$) | | | |
|---|---|---|---|---|
| | 0–30.5 cm | | 0–122 cm | |
| *Previously Cultivated site A*; 1996 | | | | |
| Initial (1969) | 45.0 | Decline over 27 year | 70.1 | Decline over 27 year |
| Plow | 30.6 | −14.4 (530)[a] | 59.2 | −10.9 (400) |
| Sub-till | 31.3 | −13.7 (510) | 50.6 | −19.5 (720) |
| No-till | 33.3 | −11.7 (430) | 55.3 | −14.8 (550) |
| $LSD_5^b$ | 1.7 | | 10.2 | |
| *Native Sod site D*; *surface*–1992, *profile*–1995 | | | | |
| Sod | 56.1 | Decline vs. sod (22 year) | 115.1 | Decline vs. sod (25 year) |
| Plow | 44.4 | −11.7 (530)[a] | 91.0 | −24.1 (960) |
| Sub-till | 47.5 | −8.6 (390) | 105.4 | −9.7 (390) |
| No-till | 49.1 | −7.0 (320) | 101.6 | −13.5 (540) |
| $LSD_5^b$ | 2.2 | | 15.8 | |
| *Native Sod site C*; *surface*–1992, *profile*–1995 | | | | |
| Sod | 64.4 | Decline vs. sod (22 year) | 125.8 | Decline vs. Sod (25 year) |
| Plow | 54.5 | −9.9 (450)[a] | 112.1 | −13.7 (550) |
| Sub-till | 54.0 | −10.4 (470) | 110.3 | −15.5 (620) |
| No-till | 54.3 | −10.1 (460) | 118.3 | −7.5 (300) |
| $LSD_5^b$ | 7.4 | | 7.6 | |

[a] Values in parenthesis represent the average annual decline in soil organic C, $kg\ C\ ha^{-1}\ year^{-1}$; relative to grass at Native Sod site.
[b] Least significant difference at $P<0.05$.

C declines were measured with reference to the sod treatment.

Average annual C budgets for the fallow tillage systems at the Native Sod site (Tillage C) were estimated using estimated C inputs and actual field measurements of respiratory C losses from soil during one wheat-fallow cycle in 1993 and 1994 (Table 9). Estimated net annual C losses from this C budget were

Table 9
Estimated soil C budgets for one wheat-fallow cycle (1993/1994) and measured/simulated average annual soil C losses for the Native Sod site (Tillage C) at Sidney, NE (after Kessavalou et al., 1998)

| Carbon input or loss | Plow | Sub-till | No-till |
|---|---|---|---|
| *Estimated C budget (crop/fallow)* | | | |
| Estimated C Inputs (Crop, weeds, etc.), kg C $ha^{-1}$ 2 $year^{-1}$ | 4720 | 3786 | 4757 |
| Measured $CO_2$ soil respiration loss, kg C $ha^{-1}$ 2 $year^{-1}$ | 7592 | 7154 | 5548 |
| Estimated net annual C loss[a], kg C $ha^{-1}$ $year^{-1}$ | 1436 | 1684 | 396 |
| *Measured/simulated soil C losses*, (kg C $ha^{-1}$ $year^{-1}$) | | | |
| Simulated[b] for surface soil (0–20 cm), 1972–1992 | 550 | 500 | 400 |
| Measured for surface soil (0–30 cm)[c], 1970–1995 | 490 | 430 | 390 |
| Measured for soil profile (0–122 cm)[c], 1970–1995 | 760 | 500 | 420 |

[a] Estimated annual C loss=(2-year measured C loss – 2-year C inputs)/2.
[b] Simulated by Metherell (1994) using the CENTURY model.
[c] Average values for tillage C and D.

then compared with average annual C losses inferred from measurement/simulation of soil C loss rates over the 22 years of study. Field $CO_2$ emissions measured in 1993 and 1994 were substantially lower in no-till than in the other two treatments, leading to a lower net annual C loss that was very similar to those inferred from soil time series measurements. Simulated soil C losses obtained by Metherell (1994) using the Century model were close to those determined from soil C measurements over time, both in magnitude and in the relative effect of different tillage methods. That residue C inputs and biological oxidation rates are the major factors affecting C, loss under the given management systems at the Native Sod site is supported by close agreement between measured and simulated losses using the Century model, which does not include erosion effects on soil C loss.

## 4. Conclusions

No-till management resulted in a different environment for biological activity near the soil surface which was often cooler and wetter than that with conventional tillage management practices, especially moldboard plowing. Consequently, biological activity and organic C reserves were also concentrated near the soil surface with no-tillage and there was greater potential for immobilization of plant available N in organic forms. Although, potential exists for less aerobic microbial activity with no-till, this apparently is rarely expressed in the semi-arid environment of the Central Great Plains. Of the three winter wheat-fallow management systems under study, no-till management resulted in the greatest conservation of soil organic matter and posed the least threat to atmospheric quality relative to loss of greenhouse gases such as $CO_2$. However, regardless of tillage management practice, soil organic matter levels with winter wheat-fallow management declined at an average rate of 320–530 kg C $ha^{-1}$ $year^{-1}$. These values corresponded to a long-term loss (22–27 years) of soil organic C from the soil profile (122 cm) of from 6% to 28%, with least loss with no-till and the greatest loss with plowing. At these sites cropped to winter wheat, the total soil C losses measured to a depth of 122 cm were closely approximated by losses measured to a depth of 30.5 cm. No-till management maintains a protective surface layer of residue and partially decomposed materials near the soil surface, but it is likely that the decline in soil organic matter and associated soil quality can only be slowed by increasing C inputs to soil through use of a more intensive cropping system which increases the time of cropping and reduces the time in fallow.

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